

# The Noether number for the groups with a cyclic subgroup of index two

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## Abstract

For the finite groups with a cyclic subgroup of index two the exact degree bound for the generators of rings of polynomial invariants is determined.

## 1 Introduction

The Noether number  $\beta(G)$  of a finite group  $G$  is  $\sup_V \beta(G, V)$ , where  $V$  ranges over all finite dimensional  $G$ -modules  $V$  over a fixed base field  $\mathbb{F}$ , and  $\beta(G, V)$  is the smallest integer  $d$  such that the algebra  $\mathbb{F}[V]^G := \{f \in \mathbb{F}[V] : f^g = f \ \forall g \in G\}$  of polynomial invariants is generated by its elements of degree at most  $d$ . By Noether's classic result [9] we have  $\beta(G) \leq |G|$  if  $\text{char}(\mathbb{F}) = 0$ , and Fleischmann [4] and Fogarty [5] proved the same inequality when  $\text{char}(\mathbb{F})$  does not divide the order of  $G$ . Recently, it has been proved that —apart from four particular groups of small order— the inequality  $\beta(G) \geq \frac{1}{2}|G|$  holds only if  $G$  is cyclic or  $G$  has a cyclic subgroup of index two (see Theorem 1.1 in [2]). It is well known and easy to see that for the cyclic group  $Z_n$  we have  $\beta(Z_n) = n$ . The main result of the present article is Theorem 10.3, giving the precise value of  $\beta(G)$  for every non-cyclic group containing a cyclic subgroup of index 2. It turns out that for these groups the difference  $\beta(G) - \frac{1}{2}|G|$  equals 1 or 2. Despite the longstanding interest in the Noether number of finite groups, there are relatively few groups for which the exact value is known. It is of some interest therefore that a few infinite series of groups is added now to the list of groups with known Noether number.

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\*The paper is based on results from the PhD thesis of the first author written at the Central European University.

†The second author is partially supported by OTKA NK81203 and K101515.

A remarkable consequence of Theorem 10.3 and the main result of [2] is that for any constant  $c > 1/2$ , up to isomorphism there are only finitely many non-cyclic groups  $G$  with  $\beta(G)/|G| > c$ , whereas there are infinitely many isomorphism classes of groups  $G$  with  $\beta(G)/|G| > 1/2$ . In particular,  $1/2$  is a limit point in the set  $\{\beta(G)/|G| : G \text{ is a finite group}\} \subset \mathbb{Q}$ , and there are no other limit points between  $1/2$  and  $1$ .

In Section 2 we recall the generalized Noether numbers  $\beta_k(G)$  and some related reduction lemmata introduced in [2]. They play an essential role in the proof of Theorem 10.3. In Section 3 we give a general lower bound on the Noether number of a group  $G$  with a normal subgroup  $N$  such that  $G/N$  is abelian, in terms of the Noether numbers of  $N$  and  $G/N$ . In the following sections we investigate the generalized Noether numbers of various groups; in the last section these results will be combined with the aid of the reduction lemmata to yield a proof of the main result. First the appearance of zero-sum sequences in the problem is explained in Section 4. The dihedral group  $D_{2n}$  and some relatives are investigated in Section 5. Moreover, some additional information on the indecomposable invariants of degree  $\beta(D_{2n})$  is derived in Section 6, that is the basis of computation of the Noether number of certain central extensions of  $D_{2n}$ . The groups  $Z_r \rtimes_{-1} Z_{4d}$  (where  $r$  and  $4d$  are co-prime integers,  $r \geq 3$ ) are treated in Section 8 by the so-called contraction method, that seems to be applicable in other situations. (A necessary combinatorial statement is proved in the previous Section 7.) The direct product of the quaternion group of order 8 and an odd order cyclic group needs a separate treatment performed in Section 9. Finally, after recalling the list of the groups with a cyclic subgroup of index 2, in Section 10 we combine the results in the earlier sections to derive the main result Theorem 10.3, giving the exact value of the generalized Noether numbers for each non-cyclic group with a cyclic subgroup of index 2.

## 2 Preliminaries

Throughout this paper  $\mathbb{F}$  denotes our base field, and  $G$  will be a finite group with  $\text{char}(\mathbb{F}) \nmid |G|$ . By a  $G$ -module we mean here a finite dimensional  $\mathbb{F}$ -vector space endowed with a linear action of the finite group  $G$ . Note that  $\beta(G)$  is unchanged if we replace  $\mathbb{F}$  by its algebraic closure, therefore we shall assume that  $\mathbb{F}$  is algebraically closed. Given a finitely generated graded module  $M = \bigoplus_{d=0}^{\infty} M_d$  over a commutative graded  $\mathbb{F}$ -algebra  $R = \bigoplus_{d=1}^{\infty} R_d$  with  $R_0 = \mathbb{F}$  and  $s \in \mathbb{N}$  write  $M_{\leq s} := \bigoplus_{d=0}^s M_d$  and  $M_{\geq s} := \bigoplus_{d=s}^{\infty} M_d$ . For a positive integer  $k$  define

$$\beta_k(M, R) := \min\{s \in \mathbb{N} \mid M \text{ is generated as an } R_+^k\text{-module by } M_{\leq s}\}$$

where  $R_+^k$  is the  $k$ -th power of the maximal homogeneous ideal  $R_+ := \bigoplus_{d=1}^{\infty} R_d$  of  $R$ . By the graded Nakayama Lemma  $\beta_k(M, R)$  is the maximal degree of a non-zero homogeneous component of the factor space  $M/R_+^k M$  (inheriting the grading from  $M$ ). Viewing  $R_+$  as an  $R$ -module we write

$$\beta_k(R) := \beta_k(R_+, R).$$

The *generalized Noether numbers* of the finite group  $G$  were introduced in [2] as follows: for a  $G$ -module  $V$  write

$$\beta_k(G, V) := \beta_k(\mathbb{F}[V]^G)$$

where  $\mathbb{F}[V]$  is the symmetric tensor algebra of  $V^*$ , the dual of  $V$ , so  $\mathbb{F}[V]$  is a  $\dim(V)$ -variable polynomial ring endowed with its standard grading. In particular,  $\mathbb{F}[V]_1 = V^*$ . Moreover, set

$$\beta_k(G) := \sup_V \beta_k(G, V)$$

where  $V$  ranges over all  $G$ -modules over  $\mathbb{F}$ . In the special case  $k = 1$  we recover the Noether number. The finiteness of  $\beta_k(G)$  follows from the obvious inequality  $\beta_k(G) \leq k\beta(G)$ ; this inequality is strict in general (see [3] for more information in this respect), and the usefulness of the concept of the generalized Noether numbers stems from the following statements proved in [2] (below for subsets  $S, T$  in a commutative  $\mathbb{F}$ -algebra we write  $ST$  for the  $\mathbb{F}$ -vector space spanned by  $\{st \mid s \in S, t \in T\}$ , and  $S^d := S \dots S$  (with  $d$  factors):

**Lemma 2.1.** *Let  $H$  be a subgroup of  $G$  and  $V$  a  $G$ -module.*

- (i) *We have  $(\mathbb{F}[V]_+^H)^{[G:H]} \subseteq \mathbb{F}[V]_+^H \mathbb{F}[V]_+^G + \mathbb{F}[V]_+^G$ .*
- (ii) *We have  $\beta_k(\mathbb{F}[V]_+, \mathbb{F}[V]^G) \leq \beta_{k[G:H]}(\mathbb{F}[V]_+, \mathbb{F}[V]^H)$ . In particular,*

$$\beta_k(G, V) \leq \beta_{k[G:H]}(H, V).$$

- (iii) *If  $H$  is normal in  $G$ , then  $\beta_k(G, V) \leq \beta_{\beta_k(G/H)}(H, V)$ .*

For later use we recall the *relative transfer map*

$$\tau_H^G(u) = \sum_{i=1}^n u^{g_i}$$

where  $g_1, \dots, g_n$  is a system of right  $H$ -coset representatives in  $G$ . (In the special case when  $H$  is the 1-element subgroup of  $G$  we write  $\tau^G$  instead of  $\tau_{\{1\}}^G$ .) The map  $\tau_H^G$  is a graded  $\mathbb{F}[V]^G$ -module epimorphism from  $\mathbb{F}[V]^H$  onto  $\mathbb{F}[V]^G$ . We shall use this fact most frequently in the following form:

**Proposition 2.2.** *We have  $\beta_k(G, V) \leq \beta_k(\mathbb{F}[V]_+^H, \mathbb{F}[V]^G)$ .*

It was shown in [11] that for an abelian group  $A$  we have  $\beta(A) = D(A)$ , the Davenport constant of  $A$ , defined as the maximal length of an irreducible zero-sum sequence over  $A$ . (For definitions and notation related to zero-sum sequences see Section 4.) The generalized Noether number also has its ancestor for abelian groups, namely  $\beta_k(A) = D_k(A)$ , the  $k$ th generalized Davenport constant of  $A$  introduced in [8] as the maximal length of a zero-sum sequence over  $A$  that does not factor as the product of  $k+1$  non-empty zero-sum sequences over  $A$ .

### 3 A lower bound

Schmid [11] proved that the Noether number is monotone with respect to taking subgroups. This extends for the generalized Noether number as well:

**Lemma 3.1.** *Let  $W$  be a finite dimensional  $H$ -module, where  $H$  is a subgroup of a finite group  $G$ , and denote by  $V$  the  $G$ -module induced from  $W$ . Then the inequality  $\beta_k(G, V) \geq \beta_k(H, W)$  holds for all positive integers  $k$ .*

*Proof.* View  $W$  as an  $H$ -submodule of

$$V = \bigoplus_{g \in G/H} gW \quad (1)$$

where  $G/H$  stands for a system of left  $H$ -coset representatives. Restriction of functions from  $V$  to  $W$  is a graded  $\mathbb{F}$ -algebra surjection  $\phi : \mathbb{F}[V] \rightarrow \mathbb{F}[W]$ . Clearly  $\phi$  is  $H$ -equivariant, hence maps  $\mathbb{F}[V]^G$  into  $\mathbb{F}[W]^H$ . Even more, as observed in the proof of Proposition 5.1 of [11], we have  $\phi(\mathbb{F}[V]^G) = \mathbb{F}[W]^H$ : indeed, the projection from  $V$  to  $W$  corresponding to the direct sum decomposition (1) identifies  $\mathbb{F}[W]$  with a subalgebra of  $\mathbb{F}[V]$ , and for an arbitrary  $f \in \mathbb{F}[W]^H \subset \mathbb{F}[W] \subset \mathbb{F}[V]$ , we get that  $\tau(f) := \sum_{g^{-1} \in G/H} f^g \in \mathbb{F}[V]^G$  is a  $G$ -invariant mapped to  $f$  by  $\phi$ . Hence if  $\mathbb{F}[V]_d^G \subseteq (\mathbb{F}[V]_+^G)^{k+1}$  for some integer  $d > 0$  then  $\mathbb{F}[W]_d^H = \phi(\mathbb{F}[V]_d^G) \subseteq \phi((\mathbb{F}[V]_+^G)^{k+1}) = (\mathbb{F}[W]_+^H)^{k+1}$ . By definition of the generalized Noether number we get that  $\beta_k(G, V) \geq \beta_k(H, W)$ .  $\square$

**Corollary 3.2.** *Let  $H$  be a subgroup of a finite group  $G$ . Then for all positive integers  $k$  we have the inequality  $\beta_k(H) \leq \beta_k(G)$ .*

Next we give a strengthening of Corollary 3.2 in the special case when  $H$  is normal in  $G$  and the factor group  $G/H$  is abelian. For a character  $\theta \in \widehat{G/H}$  denote by  $\mathbb{F}[V]^{G, \theta}$  the space  $\{f \in \mathbb{F}[V] \mid f^g = \theta(g)f \ \forall g \in G\}$  of the *relative  $G$ -invariants of weight  $\theta$* . Generalizing the construction in the proof of Lemma 3.1, for  $f \in \mathbb{F}[W]^H \subset \mathbb{F}[V]$  (here again  $V = \text{Ind}_H^G W$ ) set

$$\tau^\theta(f) := \sum_{g^{-1} \in G/H} \theta(g)^{-1} f^g \in \mathbb{F}[V]^{G, \theta}.$$

Then  $\phi(\tau^\theta(f)) = f$ , hence

$$\phi(\mathbb{F}[V]^{G, \theta}) = \mathbb{F}[W]^H \text{ holds for all } \theta \in \widehat{G/H}. \quad (2)$$

Let  $U := \bigoplus_{i=1}^d U_i$  be a direct sum of one-dimensional  $G/H$ -modules  $U_i$ . Making the identification  $\mathbb{F}[U \oplus V] = \mathbb{F}[U] \otimes \mathbb{F}[V] = \bigoplus_{\alpha \in \mathbb{N}_0^d} x^\alpha \otimes \mathbb{F}[V]$ , where the variables  $x_1, \dots, x_d$  in  $\mathbb{F}[U]$  are  $G/H$ -eigenvectors with weight denoted by  $\theta(x_i)$  (see the conventions in Section 4), we have

$$\mathbb{F}[U \oplus V]^G = \bigoplus_{\alpha \in \mathbb{N}_0^d} x^\alpha \otimes \mathbb{F}[V]^{G, -\theta(x^\alpha)} \quad (3)$$

Setting  $\tilde{\phi} := \text{id} \otimes \phi : \mathbb{F}[U \oplus V] \rightarrow \mathbb{F}[U] \otimes \mathbb{F}[W]$ , (2) and (3) imply that

$$\tilde{\phi}(\mathbb{F}[U \oplus V]_+^G) = \mathbb{F}[U]_+^G \oplus \bigoplus_{\alpha \in \mathbb{N}_0^d} x^\alpha \otimes \mathbb{F}[W]_+^H. \quad (4)$$

**Theorem 3.3.** *Let  $H$  be a normal subgroup of a finite group  $G$  with  $G/H$  abelian. Then for all positive integers  $k$  we have the inequality*

$$\beta_k(G) \geq \beta_k(H) + D(G/H) - 1.$$

*Proof.* Take  $W, V, U = \bigoplus_{i=1}^d U_i$  as above, where we have  $\beta_k(H) = \beta_k(H, W)$  in addition, and the characters  $\theta_1, \dots, \theta_d$  of the summands  $U_i$  constitute a maximal length zero-sum free sequence over the abelian group  $\widehat{G/H}$  (see Section 4 for zero-sum sequences). In particular,  $d = D(G/H) - 1$  (since  $\mathbb{F}$  is assumed to be algebraically closed). Choose a homogeneous  $H$ -invariant  $f \in \mathbb{F}[W]_+^H$  of degree  $\beta_k(H, W)$ , not contained in  $(\mathbb{F}[W]_+^H)^{k+1}$ , and consider the  $G$ -invariant

$$t := x_1 \cdots x_d \otimes \tau^\theta(f) \in \mathbb{F}[U \oplus V]^G,$$

where  $\theta = \sum_{i=1}^d \theta_i$  (we write the character group  $\widehat{G/H}$  additively). Then  $t \in \mathbb{F}[U \oplus V]^G$  is homogeneous of degree  $d + \beta_k(H, W)$ . We will show that  $t \notin (\mathbb{F}[U \oplus V]_+^G)^{k+1}$ , implying  $\beta_k(G, U \oplus V) \geq \beta_k(H, W) + d = \beta_k(H) + d$ . Indeed, assume to the contrary that  $t \in (\mathbb{F}[U \oplus V]_+^G)^{k+1}$ . Then by (4) we have

$$x_1 \cdots x_d \otimes f = \tilde{\phi}(t) \in \left( \mathbb{F}[U]_+^G \oplus \bigoplus_{\alpha \in \mathbb{N}_0^d} x^\alpha \otimes \mathbb{F}[W]_+^H \right)^{k+1}.$$

Since  $\mathbb{F}[U]_+^G$  is spanned by monomials not dividing the monomial  $x_1 \cdots x_d$  (recall that  $\theta_1, \dots, \theta_d$  is a zero-sum free sequence), we conclude that

$$x_1 \cdots x_d \otimes f \in \left( \bigoplus_{\alpha \in \mathbb{N}_0^d} x^\alpha \otimes \mathbb{F}[W]_+^H \right)^{k+1}. \quad (5)$$

Denote by  $\rho : \mathbb{F}[U] \otimes \mathbb{F}[V] \rightarrow \mathbb{F}[V]$  the  $\mathbb{F}$ -algebra homomorphism given by the specialization  $x_i \mapsto 1$  ( $i = 1, \dots, d$ ). Applying  $\rho$  to (5) we get that  $f \in (\mathbb{F}[W]_+^H)^{k+1}$ , contradicting the choice of  $f$ .  $\square$

**Remark 3.4.** (i) *The proof of Theorem 3.3 also yields the stronger conclusion*

$$\beta_k(G) \geq \max_{0 \leq s \leq k-1} \beta_{k-s}(H) + D_{s+1}(G/H) - 1 \quad (6)$$

(ii) *If  $G$  is abelian, we get  $D_k(G) \geq D_k(H) + D(G/H) - 1$  for any subgroup  $H \leq G$ . For the case  $G = H \oplus H_1$ , this was proved in [8], Proposition 3 (i).*

## 4 The role of zero-sum sequences

In the rest of the paper we shall deal with the following situation: there is a distinguished non-trivial abelian normal subgroup  $A$  in  $G$ , and any  $G$ -module  $V$  has an  $A$ -eigenbasis permuted up to non-zero scalar multiples by  $G$ . This holds for example when  $A$  is an index two subgroup, since then an irreducible  $G$ -module is either 1-dimensional or is induced from a 1-dimensional  $A$ -module. We shall always tacitly assume that our variables  $x_1, \dots, x_n$  are permuted up to non-zero scalar multiples by  $G$  and  $x_i^a = \theta_i(a)x_i$  for all  $a \in A$ , where  $\theta_i : A \rightarrow \mathbb{F}^\times$  is a character of  $A$ , called the *weight* of  $x_i$ . The set of characters of  $A$  is denoted by  $\hat{A}$ ; there is a (non-canonic) isomorphism  $\hat{\hat{A}} \cong A$  of abelian group, and we shall write  $\hat{A}$  additively. Let  $M(V)$  denote the set of monomials in  $\mathbb{F}[V]$ ; this is a monoid with respect to ordinary multiplication and unit element 1. On the other hand we denote by  $\mathcal{M}(\hat{A})$  the free commutative monoid generated by the elements of  $\hat{A}$ . Define a monoid homomorphism  $\Phi : M(V) \rightarrow \mathcal{M}(\hat{A})$  by sending each variable  $x_i$  to its weight  $\theta_i$ . We shall call  $\Phi(m)$  the *weight sequence* of the monomial  $m \in M(V)$ .

An element  $S \in \mathcal{M}(\hat{A})$  can be interpreted as a *sequence*  $S := (s_1, \dots, s_n)$  of elements of  $\hat{A}$  where their order is disregarded and repetition of elements is allowed; we call the number occurrences of an element its *multiplicity* in  $S$ . The *length* of  $S$  is  $|S| := n$ . By a *subsequence* of  $S$  we mean  $S_J := (s_j \mid j \in J)$  for some subset  $J \subseteq \{1, \dots, n\}$ . Given a sequence  $R$  over an abelian group  $A$  we write  $R = R_1 R_2$  if  $R$  is the concatenation of its subsequences  $R_1, R_2$ , and we call the expression  $R_1 R_2$  a *factorization* of  $R$ . Given an element  $a \in A$  and a positive integer  $r$ , write  $(a^r)$  for the sequence in which  $a$  occurs with multiplicity  $r$ . For an automorphism  $b$  of  $A$  and a sequence  $S = (s_1, \dots, s_n)$  we write  $S^b$  for the sequence  $(s_1^b, \dots, s_n^b)$ , and we say that the sequences  $S$  and  $T$  are *similar* if  $T = S^b$  for some  $b \in \text{Aut}(A)$ .

Let  $\theta : \mathcal{M}(\hat{A}) \rightarrow \hat{A}$  be the monoid homomorphism which assigns to each sequence over  $\hat{A}$  the sum of its elements. The value  $\theta(\Phi(m)) \in \hat{A}$  is called the *weight of the monomial*  $m \in M(V)$  and it will be abbreviated by  $\theta(m)$ . The sequence  $S$  is a *zero-sum sequence* if  $\theta(S) = 0$ . Our interest in zero-sum sequences and the related results in additive number theory stems from the observation that the invariant ring  $\mathbb{F}[V]^A$  is spanned as a vector space by all those monomials for which  $\Phi(m)$  is a zero-sum sequence over  $\hat{A}$ . Moreover, as an algebra,  $\mathbb{F}[V]^A$  is minimally generated by those monomials  $m$  for which  $\Phi(m)$  does not contain any proper zero-sum subsequences. These are called *irreducible* zero-sum sequences. A sequence is *zero-sum free* if it has no non-empty zero-sum subsequence. See for example [7] for a survey on zero-sum sequences.

## 5 Groups of dihedral type

**Definition 5.1.** A sequence  $C$  over an abelian group  $A$  is called a *zero-corner* if  $C$  has a factorization  $C = EFH$  into non-empty subsequences  $E, F, H$  such that  $EF$  and  $EH$  are zero-sum sequences. We denote by  $\rho(C)$  the minimal value of

$\max\{|EF|, |EH|, |FH|\}$  over all factorizations  $C = EFH$  satisfying the above properties, and we call it the diameter of  $C$ .

**Lemma 5.2.** *Let  $S = (s_1, \dots, s_l)$  be a sequence over  $A$  consisting of non-zero elements. Suppose that  $S$  contains a maximal zero-sum free subsequence of length  $d \leq l - 3$ . Then  $S$  contains a zero-corner  $C$  with  $\rho(C) \leq d + 1$ .*

*Proof.* For  $I \subseteq \{1, \dots, l\}$  we denote by  $S_I$  the subsequence  $(s_i : i \in I)$ . We may suppose that a maximal zero-sum free subsequence of  $S$  is  $S_J$  where  $J = \{1, \dots, d\}$ . For each  $i = 1, 2, 3$  a nonempty subset  $H_i \subseteq J \cup \{d+i\}$  exists such that  $S_{H_i}$  is an irreducible zero-sum sequence and  $d+i \in H_i$ . Observe that  $|H_i| \geq 2$  as the zero-sum sequence  $S_{H_i}$  must consist of non-zero elements. There are two cases:

- (i) If the three sets  $H_i$  are pairwise disjoint then  $C := S_{H_1} S_{H_2} S_{H_3}$  is a zero-corner with  $\rho(C) \leq d + 3 - \min\{|H_1|, |H_2|, |H_3|\} \leq d + 1$ .
- (ii) Otherwise, if e.g.  $H_1 \cap H_2 \neq \emptyset$  then  $C := S_{H_1 \cup H_2}$  is a zero-corner with  $\rho(C) \leq \max\{|H_1|, |H_2|, d + 2 - |H_1 \cap H_2|\} \leq d + 1$ ; indeed,  $C = EFH$  with  $E := S_{H_1 \cap H_2}$ ,  $F := S_{H_1 \setminus H_2}$ ,  $H := S_{H_2 \setminus H_1}$ .  $\square$

We turn now to a semidirect product  $G = A \rtimes_{-1} Z_2$  where  $A$  is a non-trivial abelian group and  $Z_2 = \langle b \rangle$  acting on it by inversion (in particular, when  $A = Z_n$  is the cyclic group of order  $n$ , we obtain the dihedral group  $D_{2n}$  of order  $2n$ ). Keeping conventions, notations and terminology introduced in Sections 2 and 4, let  $W$  be a  $G$ -module over  $\mathbb{F}$ ,  $I = \mathbb{F}[W]^A$ ,  $R = \mathbb{F}[W]^G$  and  $\tau := \tau_A^G : I \rightarrow R$  is the relative transfer map.

**Proposition 5.3.** *For any monomial  $m \in I$  and integer  $k \geq 0$  it holds that  $m \in I_+ R_+^k$  provided that*

- (i)  $\deg(m) \geq k D(A) + 2$ , or
- (ii)  $\deg(m) \geq (k - 1) D(A) + d + 2$  where  $\Phi(m)$  contains a zero-corner with diameter  $d$

*Proof.* We apply induction on  $k$ . The case  $k = 0$  is trivial so we may suppose  $k \geq 1$ . Assume condition (ii). Thus  $m = nr$  where the monomial  $n = efh$  is such that  $ef$  and  $eh$  are  $A$ -invariant monomials, and  $\max\{\deg(ef), \deg(eh), \deg(fh)\} = d$ . Denoting  $\theta(e)$  by  $a \in \hat{A}$  we have  $\theta(f) = \theta(h) = -a$  and  $\theta(r) = \theta(e) = a$ . The generator  $b$  of  $Z_2$  transforms each monomial of weight  $a$  into a monomial of weight  $-a$ , and vice versa, hence  $fh^b$  and  $e^b r$  are both  $A$ -invariant. Given that  $b^2 = 1$  the following relation holds:

$$2m = \tau(ef)hr + \tau(eh)fr - \tau(fh^b)e^b r. \quad (7)$$

After division by  $2 \in \mathbb{F}^\times$  we get from (7) that  $m \in I_{\geq \deg(m)-d}(R_+)_{\leq d}$ . Given that  $\deg(m) - d \geq (k - 1) D(A) + 2$  by assumption, the induction hypothesis applies, whence  $I_{\geq \deg(m)-d} \subseteq R_+^{k-1} I_+$  and  $m \in I_+ R_+^k$  as claimed. Suppose next

that condition (i) holds. If  $m$  contains three  $A$ -invariant variables, then  $\Phi(m)$  contains the zero corner  $(0, 0, 0)$  with diameter 2, hence we are back in case (ii). Otherwise  $\Phi(m)$  contains a subsequence of length at least  $k D(A)$  of non-zero elements. If  $k > 1$ , then by Lemma 5.2  $\Phi(m)$  has a zero-corner of diameter at most  $D(A)$ , so again we are back in case (ii). It remains that  $k = 1$ . If  $m$  contains one or two  $A$ -invariant variables, then  $m \in I_+^3 \subseteq I_+ R_+$  by Lemma 2.1. Otherwise  $m$  contains a subsequence of length at least  $D(A) + 2$  of non-zero elements, hence by Lemma 5.2  $\Phi(m)$  contains a zero-corner of diameter at most  $D(A)$ . We are done by case (ii).  $\square$

**Theorem 5.4.** *Let  $G = A \rtimes_{-1} Z_2$  and suppose  $|G| \in \mathbb{F}^\times$ . Then*

$$D_k(A) + 1 \leq \beta_k(G) \leq k D(A) + 1$$

*Proof.* By Proposition 2.2 we have  $\beta_k(G, W) \leq \beta_k(I_+, R)$ . Since  $I_d \subseteq I_+ R_+^k$  for  $d \geq k D(A) + 2$  by Proposition 5.3, it follows that  $\beta_k(I_+, R) \leq k D(A) + 1$ . The lower bound is given by Theorem 3.3.  $\square$

If  $k = 1$  then  $D_1(A) = D(A)$  and if  $A = Z_n$  is cyclic then  $D_k(Z_n) = k D(Z_n)$ , hence we obtain the following immediate consequences:

**Corollary 5.5.** *For any abelian group  $A$  we have  $\beta(A \rtimes_{-1} Z_2) = D(A) + 1$ .*

**Corollary 5.6.** *For the dihedral group  $D_{2n}$  of order  $2n$  and an arbitrary positive integer  $k$  we have  $\beta_k(D_{2n}) = nk + 1$ , provided that  $2n \in \mathbb{F}^\times$ .*

The special case  $k = 1$  of Corollary 5.6 is due to Schmid [11] when  $\text{char}(\mathbb{F}) = 0$  and to Sezer [12] in non-modular positive characteristic.

## 6 Extremal invariants

Let  $A$  be an abelian normal subgroup in a finite group  $G$ , and assume the conditions and conventions from the beginning of Section 4.

**Definition 6.1.** *Let  $R = \mathbb{F}[V]^G$ ; a monomial  $u \in \mathbb{F}[V]^A$  will be called  $k$ -extremal with respect to  $\tau_A^G$  if  $\deg(u) = \beta_k(G)$  while  $\tau_A^G(u) \notin R_+^{k+1}$ . A sequence  $S$  over  $\hat{A}$  is  $k$ -extremal if there is a  $G$ -module  $V$  and a monomial  $m \in \mathbb{F}[V]^A$  with  $\Phi(m) = S$  such that  $m$  is  $k$ -extremal with respect to  $\tau_A^G$ .*

For any sequence  $S = (s_1, \dots, s_d)$  over an abelian group  $A$  the set of its partial sums is

$$\Sigma(S) := \left\{ \sum_{i \in I} s_i : I \subseteq \{1, \dots, d\} \right\}.$$

**Lemma 6.2.** *Let  $p$  be a prime and  $S = (s_1, \dots, s_d)$  a sequence of non-zero elements of  $Z_p$ . Then  $|\Sigma(S)| \geq \min\{p, d + 1\}$ .*

*Proof.* This is a well known and easy consequence of the Cauchy-Davenport Theorem, asserting that  $|C + D| \geq \min\{p, |C| + |D| - 1\}$  for any non-empty subsets  $C, D$  in  $Z_p$ , where  $p$  is a prime.  $\square$



**Lemma 6.3.** (Freeze – Smith [6]) For any zero-sum free sequence  $S$  over  $Z_n$  of length  $d$  and maximal multiplicity  $h = h(S)$  it holds that

$$|\Sigma(S)| \geq 2d - h + 1.$$

**Proposition 6.4.** Let  $G = A \rtimes_{-1} Z_2 = D_{2n}$  be the dihedral group of order  $2n$  where  $n \geq 3$ . A sequence over  $\hat{A} \cong Z_n$  is  $k$ -extremal with respect to  $\tau_A^G$  only if it has the form  $(0, a^{kn})$  for some generator  $a$  of  $\hat{A}$ .

*Proof.* Let  $m \in \mathbb{F}[W]^A$  be a monomial of  $\deg(m) = \beta_k(D_{2n}) = kn + 1$  such that  $\tau_A^G(m) \notin R_+^{k+1}$ . If  $m$  is divisible by the product of two weight zero variables, then  $m \in R_+ I_{\geq kn-1}$  by Lemma 2.1. Since  $kn - 1 > \beta_{k-1}(D_{2n})$ , we get  $\tau_A^G(m) \in R_+ \tau_A^G(I_{>\beta_{k-1}(D_{2n})}) \subseteq R_+^{k+1}$ , a contradiction. It remains that the multiplicity of 0 in  $\Phi(m)$  is at most one. Let  $H \subseteq Z_n$  be the set of nonzero values occurring in  $\Phi(m)$ . Suppose  $|H| \geq 2$ ; if  $\Phi(m)$  contains a zero-corner of the form  $(w, w, -w)$  with diameter 2, then  $\tau(m) \in R_+^{k+1}$  by Proposition 5.3 (ii), a contradiction. We are done if  $n = 3$ , so assume for the rest that  $n \geq 4$ . Then  $\Phi(m)$  contains a zero-sum free subsequence of length 2, consisting of two distinct elements. By Lemma 6.3 this extends to a maximal zero-sum free subsequence of length at most  $n - 2$ . If  $k > 1$  or  $0 \notin \Phi(m)$ , then  $\tau(m) \in R_+^{k+1}$  by Lemma 5.2 and Proposition 5.3, a contradiction. If  $k = 1$  and  $0 \in \Phi(m)$ , then  $m \in I_+^3$ , hence  $\tau(m) \in R_+^2$  by Lemma 2.1, a contradiction again. Consequently  $|H| = 1$  and  $\Phi(m) = (0, a^{kn})$ . Taking into account Lemma 2.1,  $a$  must have order  $n$ , whence our claim.  $\square$

## 7 A result on zero-sum sequences

Let  $e$  be a generator of the cyclic group  $Z_n$ ; for an arbitrary element  $a \in Z_n$ , the smallest positive integer  $r$  such that  $a = re$  is denoted by  $\|a\|_e$ . For any sequence  $S = (a_1, \dots, a_l)$  over  $Z_n$  we set  $\|S\|_e := \|a_1\|_e + \dots + \|a_l\|_e$ .

The following two statements are based on an intermediary step in the proof of the Savchev – Chen Theorem (see Proposition 2. in [10]):

**Proposition 7.1.** Let  $S_1 \subset S_2 \subset \dots \subset S_t$  be zero-sum free sequences over the cyclic group  $Z_n$  such that  $|S_i| = i$  for all  $i = 1, \dots, t$  and

$$|\Sigma(S_{i+1})| \geq |\Sigma(S_i)| + 2 \quad \text{for all } i \leq t - 1 \quad (8)$$

If moreover  $S_t(b)$  is also zero-sum free for some  $b \in Z_n$  and  $|\Sigma(S_t(b))| = |\Sigma(S_t)| + 1$ , then  $b$  is the unique element with these two properties.

**Lemma 7.2.** Any sequence  $S$  over  $Z_n$  contains either a zero-sum sequence of length at most  $\lceil \frac{n}{2} \rceil$  or an element of multiplicity at least  $|S| - \lfloor \frac{n}{2} \rfloor$ .

*Proof.* Suppose that  $S$  does not contain a zero-sum sequence of length at most  $\lceil \frac{n}{2} \rceil$  and let  $S_1 \subset \dots \subset S_t$  be zero-sum free sequences where  $t$  is maximal with the property that  $|\Sigma(S_{i+1})| \geq |\Sigma(S_i)| + 2$  and  $|S_i| = i$  for every  $i \leq t - 1$ ; let

$S = S_t R$ . By this assumption  $n \geq |\Sigma(S_t)| \geq 2t$ . If  $t = \lceil \frac{n}{2} \rceil$ , which enforces that  $n$  is even, then  $|\Sigma(S_t)| = n$ , hence any  $a \in R$  can be completed into a zero-sum sequence  $U(a)$  with some  $U \subseteq S_t$ . By our assumption it is necessary that  $|U(a)| > \lceil \frac{n}{2} \rceil$ , hence  $U = S_t$  and the multiplicity of  $a = -\theta(S_t)$  is at least  $|R| = |S| - \frac{n}{2}$ . It remains that  $t \leq \lceil \frac{n}{2} \rceil - 1$ . Then for any  $b \in R$  the sequence  $S_t(b)$  of length at most  $\lceil \frac{n}{2} \rceil$  must be zero-sum free by our assumption, hence by the maximality property of  $S_t$  necessarily  $|\Sigma(S(b))| = |\Sigma(S)| + 1$ . But we know from Proposition 7.1 that the element  $b$  with these two properties is unique, hence  $b$  has multiplicity  $|R| \geq |S| - \lceil \frac{n}{2} \rceil + 1$ .  $\square$

**Lemma 7.3.** *Let  $S$  be a zero-sum sequence over  $Z_n$  of length  $|S| \geq kn + 1$  where  $k \geq 2$ , which does not factor into more than  $k + 1$  non-empty zero-sum sequences. Then  $S = T_1 T_2 (e^{(k-1)n})$  where  $\langle e \rangle = Z_n$  and  $\|T_1\|_e = \|T_2\|_e = n$ .*

*Proof.* First we prove that an element  $e \in S$  has multiplicity at least  $(k-1)n$ ; if so  $e$  will have order  $n$ , for otherwise  $S$  factors into at least  $2(k-1) + 2 > k+1$  non-empty zero-sum sequences. Let  $S = T_1 S_1$  where  $T_1$  is a non-empty zero-sum sequence of minimal length in  $S$ . If  $|T_1| > \lceil \frac{n}{2} \rceil$  then  $h(S) \geq |S| - \lfloor \frac{n}{2} \rfloor$  by Lemma 7.2, and we are done. If however  $|T_1| \leq \lceil \frac{n}{2} \rceil$  then  $S_1 = T_2 S_2$  where  $T_2$  is a minimal non-empty zero-sum sequence in  $S_1$ ; obviously  $|T_2| \geq |T_1|$ . If  $|T_2| > \lceil \frac{n}{2} \rceil$  then  $h(S) \geq h(S_1) \geq |S_1| - \lfloor \frac{n}{2} \rfloor \geq |S| - \lceil \frac{n}{2} \rceil - \lfloor \frac{n}{2} \rfloor = |S| - n$  by Lemma 7.2, and we are done again. It remains that  $|T_2| \leq \lceil \frac{n}{2} \rceil$ . Then  $|T_1 T_2| \leq n + 1$  and  $|S_2| \geq (k-1)n$ . Given that  $S_2$  cannot be factored into more than  $k-1$  non-empty zero-sum sequences it is necessary that  $S_2 = (e^{(k-1)n})$ .

Now suppose to the contrary that  $\|T_1\|_e > n$ , say. Then  $T_1 = U(a)V$  where  $U, V$  are non-empty subsequences such that  $\|U\|_e < n$ ,  $\|U(a)\|_e > n$ . But then  $(e^n) \cdot T_1 = (e^{n-\|U\|_e})U \cdot (e^{n-\|a\|_e}a) \cdot (e^{\|U\|_e+\|a\|_e-n})V$  is a factorization which leads to a decomposition of  $S$  into more than  $k+1$  non-empty zero-sum sequences, and this is a contradiction.  $\square$

## 8 The contraction method: the groups $Z_r \rtimes_{-1} Z_{2n}$

Let  $B \leq A$  be a subgroup of an abelian group  $A$ . If  $S = (s_1, \dots, s_d)$  is a sequence over  $A$ , then  $(s_1 + B, \dots, s_d + B)$  is a sequence over  $A/B$  which will be denoted by  $S/B$ . Suppose that  $\theta(S) \in B$ ; a *B-contraction* of  $S$  is a sequence over  $B$  of the form  $(\theta(S_1), \dots, \theta(S_t))$  where  $S = S_1 \dots S_t$  and each  $S_i/B$  is an irreducible zero-sum sequence over  $A/B$ ; so indeed  $\theta(S_i) \in B$ .

Suppose that  $A$  is a non-trivial abelian normal subgroup of  $G$ . Let  $C < A$  be a subgroup such that  $C \triangleleft G$  hence  $A/C$  is a non-trivial abelian normal subgroup of  $G/C$ . Suppose moreover that any  $G$ -module has an  $A$ -eigenbasis permuted up to scalars by  $G$ , so we can apply the conventions of Section 4 both for the pair  $(G, A)$  and  $(G/C, A/C)$ . Note that  $\widehat{A/C}$  is naturally a subgroup of  $\hat{A}$ , thus the above notion of contractions can be applied based on the following observation:

**Lemma 8.1.** *For any  $G$ -module  $V$  there exists a  $G/C$ -module  $U$  and a  $G/C$ -equivariant  $\mathbb{F}$ -algebra epimorphism  $\pi : \mathbb{F}[U] \rightarrow \mathbb{F}[V]^C$  such that any monomial*

$m \in \mathbb{F}[V]^C$  has a preimage  $\tilde{m} \in \pi^{-1}(m)$  with  $\Phi(\tilde{m})$  equal to an arbitrarily prescribed  $\widehat{A/C}$ -contraction of  $\Phi(m)$ .

*Proof.* By assumption  $V^*$  has a basis  $x_1, \dots, x_n$  consisting of  $A$ -eigenvectors which are permuted up to scalars by  $G$ . Let  $M$  be the set of  $C$ -invariant monomials in these variables, and  $E \subset M$  the subset of the irreducibles among them, i.e. which cannot be factored into two non-trivial  $C$ -invariant monomials.  $\mathbb{F}[V]^C$  is minimally generated as an algebra by  $E$ . Moreover the factor group  $G/C$  has an inherited action on  $\mathbb{F}[V]^C$ , and permutes the elements of  $E$  up to non-zero scalar multiples. Define  $U$  as the dual of the  $G/C$ -invariant subspace  $\text{Span}_{\mathbb{F}}(E)$ .  $E$  is a basis of this vector space, hence  $E$  is identified with the set of variables in  $\mathbb{F}[U]$ . The  $\mathbb{F}$ -algebra epimorphism  $\pi : \mathbb{F}[U] \rightarrow \mathbb{F}[V]^C$  taking a variable to the corresponding irreducible  $C$ -invariant monomial is  $G/C$ -equivariant. Now let  $(\theta(S_1), \dots, \theta(S_l))$  be an arbitrary  $\widehat{A/C}$ -contraction of  $\Phi(m)$  for a monomial  $m \in \mathbb{F}[V]^C$ . By definition this means that  $m = m_1 \dots m_l$  where each  $m_i$  is an irreducible  $C$ -invariant monomial with  $\Phi(m_i) = S_i$ . Hence for each  $i$  there are variables  $y_1, \dots, y_l \in \mathbb{F}[U]$  such that  $\pi(y_i) = m_i$  by construction, and the monomial  $\tilde{m} := y_1 \dots y_l$  has the required property.  $\square$

Using this map  $\pi$  we can derive information on the generators of  $\mathbb{F}[V]^G$  from our preexisting knowledge about the generators of  $\mathbb{F}[U]^{G/C}$ . As an example of this principle, we will study here the group  $G := Z_r \rtimes_{-1} Z_{2n}$  where  $r$  and  $2n$  are coprime,  $r \geq 3$ , and the generator of  $Z_{2n}$  operates by inversion on  $Z_r$ . The center of  $G$  is  $C = Z_n$  and  $G/C$  is isomorphic to the dihedral group  $D_{2r}$  whose extremal monomials were described before.  $G$  has the abelian normal subgroup  $A \cong Z_{rn}$ ,  $A \geq C$  such that  $G/A = \langle b \rangle \cong Z_2$ . We will write  $S \sim S'$  for two sequences over  $\hat{A}$  if  $S = EF$  and  $S' = E^b F$  for a zero-sum sequence  $E$  of length at most  $n$ .

**Proposition 8.2.** *If  $S$  is a  $k$ -extremal sequence over  $\hat{A}$  then any  $\widehat{A/C}$ -contraction of any sequence  $S' \sim S$  is a  $k$ -extremal sequence over  $\widehat{A/C}$ .*

*Proof.* Since  $S$  is a  $k$ -extremal sequence, there is a  $G$ -module  $V$  and a monomial  $m \in \mathbb{F}[V]^A$  such that  $\Phi(m) = S$  and  $m$  is  $k$ -extremal with respect to  $\tau_A^G$ . Let  $\pi : \mathbb{F}[U]^{A/C} \rightarrow \mathbb{F}[V]^A$  denote the restriction of the map constructed in Lemma 8.1 to the  $A$ -invariants, and consider the transfer maps  $\tilde{\tau} : \mathbb{F}[U]^{A/C} \rightarrow \mathbb{F}[U]^{G/C}$ ,  $\tau : \mathbb{F}[V]^A \rightarrow \mathbb{F}[V]^G$ . The  $G/C$ -equivariance of  $\pi$  implies that  $\tau\pi = \pi\tilde{\tau}$ . Suppose first that  $S$  has a non- $k$ -extremal  $C$ -contraction  $\tilde{S}$ . Since  $|\tilde{S}| \geq \frac{1}{n}|S|$  where we have  $|S| = \beta_k(G) \geq knr + 1$  by Theorem 3.3, it follows that  $|\tilde{S}| \geq kr + 1 = \beta_k(G/C)$  by Corollary 5.6. So for the monomial  $\tilde{m} \in \mathbb{F}[U]$  with  $\pi(\tilde{m}) = m$  and  $\Phi(\tilde{m}) = \tilde{S}$ , which exists by Lemma 8.1, we have  $\tilde{\tau}(\tilde{m}) \in (\mathbb{F}[U]_+^{G/C})^{k+1}$ . But then  $\tau(m) = \pi(\tilde{\tau}(\tilde{m})) \in (\mathbb{F}[V]_+^G)^{k+1}$ , a contradiction.

Now suppose that a sequence  $S' = E^b F$  has a  $C$ -contraction  $\tilde{S}$  which is not  $k$ -extremal, where  $0 < |E| \leq n$ . Then take a factorization  $m = uv$  with  $\Phi(u) = E$  and  $\Phi(v) = F$ . By the previous argument  $\tau(u^b v) \in (\mathbb{F}[V]_+^G)^{k+1}$ . By Lemma 2.1 and Corollary 5.6 we have  $\beta_k(G) \leq \beta_{\beta_k(D_{2r})}(C) = nrk + n$ , hence

$\deg(v) = \deg(m) - |E| \geq \beta_k(G) - n \geq nrk + 1 - n > nr(k-1) + n \geq \beta_{k-1}(G)$ . Consequently  $\tau(v) \in (\mathbb{F}[V]_+^G)^k$  and  $\tau(m) = \tau(u)\tau(v) - \tau(u^b v) \in (\mathbb{F}[V]_+^G)^{k+1}$ , a contradiction again.  $\square$

In the following statement we identify  $\hat{A} = Z_{rn}$  with the additive group of  $\mathbb{Z}/rn\mathbb{Z}$  and write  $0, 1, 2, \dots$  for its elements, whenever it seems convenient.

**Lemma 8.3.** *Let  $S$  be a zero-sum sequence over  $\hat{A} = Z_{rn}$  having length at least  $nrk + 1$ , where  $k \geq 1$ ,  $n \geq 3$ ,  $r \geq 3$ , and  $r$  and  $2n$  are coprime. If any  $Z_r$ -contraction of any sequence  $S' \sim S$  is similar to  $(0, n^{rk})$  then  $S$  is similar to  $(0, 1^{nrk})$ .*

*Proof.* By assumption any  $Z_r$ -contraction of  $S$  must have length  $l := rk + 1$ . By Lemma 7.3 then  $S = T_1 \dots T_l$  where  $T_i/Z_r = (e^n)$  for every  $i \leq l-2$  and some generator  $e$  of  $Z_{rn}/Z_r \cong Z_n$ , while  $\|T_{l-1}/Z_r\|_e = \|T_l/Z_r\|_e = n$ , and we may assume that the sequence  $(\theta(T_1), \dots, \theta(T_l))$  equals  $(0, n^{rk})$ . In particular, at most one element of the sequence  $S$  belongs to  $Z_n$ , and so  $x^b \neq x$  for  $x \in S$  with at most one exception. As  $l \geq 4$  we may assume that  $\theta(T_1) \neq 0$  and let  $i \neq 1$  be any other index for which  $\theta(T_i) \neq 0$ . Take an arbitrary element  $x \in T_i$  and let  $U \subseteq T_1$  be an arbitrary subsequence of length  $d := \|x + Z_r\|_e < n$ . After exchanging the proper subsequences  $U$  and  $(x)$  in  $T_1$  and  $T_i$  the resulting  $\tilde{T}_1$  and  $\tilde{T}_i$  projects to zero-sum sequences over  $Z_n$ , so we get another  $Z_r$ -contraction of  $S$ :

$$(\theta(\tilde{T}_1), \theta(T_2), \dots, \theta(\tilde{T}_i), \dots, \theta(T_l)) = (0, n^{rk-2}, n - \delta, n + \delta)$$

where  $\delta := \theta(U) - x$ . By assumption this must be similar to  $(0, n^{rk})$  which is only possible if they are actually equal (here we used that  $l \geq 4$ ). Therefore  $\delta = 0$  and  $x = \theta(U)$ . As this holds for any subsequence  $U' \subseteq T_1$  of the same length  $d < |T_1|$ , necessarily  $T_1 = (f^n)$  for some generator  $f \in Z_{nr}$  such that  $f + Z_r = e$ . Moreover, as  $x = \theta(U) = df$ , we get by the definition of  $d$  and  $\|x\|_f$  that

$$\|x\|_f = \|x + Z_r\|_e \quad (9)$$

for every  $x \in T_i$ , where  $i$  differs from that unique index  $s$  for which  $\theta(T_s) = 0$ . Observe on the other hand that (9) cannot be true for every element  $y \in T_s$ , for otherwise  $\|T_s\|_f = \|T_s/Z_r\|_e = n$ , which is impossible, as  $\|T_s\|_f$  must be a multiple of  $nr$ . Now suppose that  $|T_s| \geq 2$  and that (9) fails for  $y \in T_s$ . Then swapping  $y$  with a proper subsequence  $U \subseteq T_1$  of length  $\|y + Z_r\|_e$  we get as before that  $\delta := \theta(U) - y = -nf$ , whence  $\|y\|_f = \|y + Z_r\|_e + n(r-1)$ . On the other hand if  $z \in T_s$  is a second element besides  $y$  for which (9) fails, then in particular  $(yz) \neq T_s$ , as otherwise calculating  $\|z\|_f$  by the same argument yields that  $\|T_s\|_f = \|T_s/Z_r\|_e + 2n(r-1) = n(2r-1)$ , which is not a multiple of  $nr$ . Now swapping  $(yz)$  with a proper subsequence of  $T_1$  of length  $\|yz + Z_r\|_e$  gives a  $Z_r$ -contraction of  $S$  of the form  $(2n, -n, n^{rk-2})$  which is not similar to  $(0, n^{rk})$ . This contradiction shows that  $y$  is unique with the property that  $\|y\|_f \neq \|y + Z_r\|_e$ . So if  $|T_s| \geq 3$  then the sequence  $S'$  obtained from  $S$  by replacing  $T_s$  with  $T_s^b$  will not satisfy this requirement: indeed,  $\|x + Z_r\|_e = \|x^b + Z_r\|_e$  for all  $x$ ,

whereas  $\|x\|_f = \|x^b\|_f$  means  $x \in Z_n \subset Z_{nr}$ . Thus  $S'$  will have  $Z_r$ -contractions not similar to  $(0, n^{rk})$ , which is a contradiction as  $S' \sim S$ . It remains that  $|T_s| = 2$  and  $T_s = (-y, y)$ . Then necessarily  $s \in \{l-1, l\}$  and  $T_1 = \dots = T_{l-2} = (f^n)$ . If moreover  $y \neq -f$  then  $n(r-1) < \|y\|_f < nr-1$  and consequently we have the factorization  $T_s T_1 = (-y, y, f^n) = (y, f^{nr-\|y\|_f})(-y, f^{\|y\|_f-n(r-1)})$  which leads us back to the case when  $|T_s| \geq 3$ . Finally, if  $y = -f$  then observe that  $f^b \neq \pm f$ , as we have  $n > 2$ ; hence after replacing  $T_s$  with  $T_s^b \neq (-f, f)$  we get back to the case when  $y \neq -f$ .

As a result of these contradictions we excluded that  $|T_s| \geq 2$ . Therefore  $|T_s| = 1$  and  $T_s = (0)$ . Then we must have  $|T_i| = n$  for every  $i \neq s$  whence  $|T_i/Z_r| = (e^n)$  follows. Using (9) this implies that  $S = (0, f^{nrk})$ .  $\square$

**Theorem 8.4.** *For the group  $G = Z_s \times (Z_r \rtimes_{-1} Z_{2^{n+1}})$ , where  $r \geq 3$ ,  $n \geq 1$  and  $r, s$  are coprime odd integers, we have  $\beta_k(G) = 2^n srk + 1$ , except if  $s = n = 1$ , in which case  $\beta_k(G) = 2rk + 2$ .*

*Proof.*  $\beta_k(G)$  is the length of a sequence  $S$  over  $A := Z_{2^n sr}$  which is  $k$ -extremal with respect to  $\tau_A^G$ . By Proposition 8.2 any  $Z_r$ -contraction of any sequence equivalent to  $S$  must be  $k$ -extremal with respect to  $\tau_{Z_r}^{D_{2r}}$ , hence it is similar to  $(0, (2^n s)^{rk})$  by Proposition 6.4. Therefore  $S$  is similar to  $(0, 1^{2^n srk})$  by Lemma 8.3, provided that  $2^n s \geq 3$ ; in particular  $\beta_k(G) = |S| = 2^n srk + 1$ .

For the case  $s = n = 1$  we have  $\beta_k(Z_r \rtimes_{-1} Z_4) \leq 2\beta_k(D_{2r}) = 2r + 2$  by Lemma 2.1 and Corollary 5.6. To see the reverse inequality consider the representation on  $V = \mathbb{F}^2$  of  $G := \langle a, b \rangle$  given by the matrices

$$a \mapsto \begin{pmatrix} \omega & 0 \\ 0 & \omega^{-1} \end{pmatrix} \quad b \mapsto \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \quad (10)$$

where  $\omega$  is a primitive  $2r$ -th root of unity and  $i = \sqrt{-1}$  a primitive fourth root of unity. Then  $\mathbb{F}[V] = \mathbb{F}[x, y]$  where  $x, y$  are the usual coordinate functions on  $\mathbb{F}^2$ . Obviously  $(xy)^2$  is invariant under  $a$  and  $b$  alike; from this it is easily seen that  $R = \mathbb{F}[V]^G$  is generated by  $(xy)^2$ ,  $\tau_A^G(x^{2r})$  and  $\tau_A^G(x^{2r+1}y)$ . This shows that any element of  $R_+^{k+1}$  not divisible by  $(xy)^2$  must have degree at least  $2r(k+1)$ . As a result  $(R_+^{k+1})_{2rk+2} \subseteq \langle (xy)^2 \rangle$ . The invariant  $\tau_A^G(x^{2rk+1}y) \in R_+$  of degree  $2rk+2$  does not belong to the ideal  $\langle (xy)^2 \rangle$  and this proves that  $\beta_k(G) \geq 2rk + 2$ .  $\square$

## 9 The quaternion group

The dicyclic group  $Dic_{4n}$  is defined for any  $n > 1$  by the presentation

$$Dic_{4n} = \langle a, b : a^{2n} = 1, b^2 = a^n, bab^{-1} = a^{-1} \rangle$$

In particular for  $n = 2$  we retrieve the quaternion group  $Q = Dic_8$ . The equality  $\beta(Q) = 6$  for  $\mathbb{F} = \mathbb{C}$  was proved in [11].

**Proposition 9.1.** *We have  $\beta_k(Dic_{4n}) = 2nk + 2$  for  $n > 1$  even and  $k \geq 1$ . Moreover if  $(r, 4n) = 1$  then  $1 \leq \beta_k(Z_r \times Dic_{4n}) - 2nrk \leq 2$ .*

*Proof.* Taking  $\omega$  a primitive  $2n$ -th root of unity in (10), the same argument as in the proof of Theorem 8.4 shows that  $\beta_k(Dic_{4n}) \geq 2nk + 2$ . Moreover for  $G := Z_r \times Dic_{4n}$  we have  $\beta_k(G) \geq 2rnk + 1$  by Theorem 3.3. Observe that  $G/Z(Dic_{4n})$  is isomorphic to  $Z_r \times D_{2n}$ , respectively to  $Z_{2r} \times Z_2$  for  $n = 2$ . Combining Lemma 2.1 with Corollary 5.6 leads to the inequality  $\beta_k(G) \leq 2nrk + 2$ .  $\square$

**Proposition 9.2.** *Let  $Q = \langle a, b \rangle$  be the quaternion group where  $A := \langle a \rangle$  is isomorphic to  $Z_4$ . If  $S$  is a zero-sum sequence over  $\hat{A}$  of length  $4k + 2$  which is  $k$ -extremal with respect to  $\tau_A^Q$  then  $S = (1^t, 3^s)$  where  $t \neq s$ .*

*Proof.* Set  $I = \mathbb{F}[V]^A$ ,  $R = \mathbb{F}[V]^Q$  and let  $S = (0^x, 2^y, 1^t, 3^s)$  be the weight sequence of a monomial  $m \in I$  of degree  $4k + 2$  such that  $\tau(m) \notin R_+^{k+1}$ . By replacing  $m$  with  $m^b$ , if needed, we may suppose that  $t \geq s$ . We will use induction on  $t - s$ . Suppose first that  $t - s \leq 4$  and consider the factorization  $S = (22)^{\lfloor y/2 \rfloor} (13)^s (0)^x T$ . If  $y$  is odd then necessarily  $T = (211)$  and  $x \geq 1$ , hence  $m \in I_+^{2k+1}$ , which is a contradiction by Lemma 2.1. If however  $y$  is even then either  $T$  is empty, and then  $m \in I_+^{2k+1}$  again, or else  $T = (1111)$ ; in this later case if  $x \geq 2$  then again  $m \in I_+^{2k+1}$  or otherwise, taking into account that  $|S|$  is even, it remains that  $x = 0$  and  $S = (2^y, 1^{s+4}, 3^s)$ . Now, if  $y > 0$  then take a factorization  $m = uv$  such that  $\Phi(u) = (211)$  and observe that  $\tau(m) = \tau(u)\tau(v) - \tau(u^b v) \in R_+^{k+1}$ , because on the one hand  $\deg(v) = 4k - 1 > \beta_{k-1}(Q)$ , while on the other hand  $\Phi(u^b v) = (2^y)(13)^{s+2}$ , hence  $u^b v \in I_+^{2k+1}$  by what has been said before. From this contradiction we conclude that  $y = 0$  and  $S = (1^{s+4}, 3^s)$  whenever  $t - s \leq 4$  holds.

Finally, if  $t - s > 4$  we have a factorization  $m = uv$  with  $\Phi(u) = (1111)$ , and since  $\tau(m) = \tau(u)\tau(v) - \tau(u^b v) \notin R_+^{k+1}$  by assumption, it is necessary that either  $\tau(v) \notin R_+^k$ , when  $\Phi(v) = (1^{t-4}, 3^s)$  by the induction hypothesis, or  $\tau(u^b v) \notin R_+^k$ , when similarly  $\Phi(u^b v) = (1^{t-4}, 3^{s+4})$ , and in both cases  $\Phi(m) = (1^t, 3^s)$ , as claimed.  $\square$

**Theorem 9.3.** *Let  $G = Z_p \times Q$  for an odd prime  $p$ . Then  $\beta_k(G) = 4pk + 1$  for every  $k \geq 1$ .*

*Proof.* Here the distinguished abelian normal subgroup is  $A := C \times B \cong Z_{4p}$ , where  $C := Z_p \triangleleft G$  and  $B := \langle a \rangle$ . Set  $L := \mathbb{F}[V]$  and  $R := L^G$ . We write  $\theta|_C$  and  $\theta|_B$  for the restriction of the character  $\theta \in \hat{A}$  to  $C$  or  $B$ , respectively, and we define accordingly  $S|_C$  and  $S|_B$  for any sequence  $S$  over  $\hat{A}$ ; note that  $\theta = (\theta|_C, \theta|_B)$  by the natural isomorphism  $\hat{A} \cong \hat{C} \times \hat{B}$ .

We already proved in Proposition 9.1 that  $1 \leq \beta_k(G) - 4kp \leq 2$ . Suppose for contradiction that there is a  $G$ -module  $V$  and a monomial  $m \in \mathbb{F}[V]^A$  with  $\deg(m) = 4pk + 2$  and  $\tau_A^G(m) \notin R_+^{k+1}$ . Given that the restriction of  $\tau_B^Q$  to  $L^A$  coincides with  $\tau_A^G$ , the sequence  $\Phi(m)|_B$  is  $kp$ -extremal: indeed, otherwise  $\tau_B^Q(m) \in (L_+^Q)^{kp+1}$  as  $\deg(m) = \beta_{kp}(Q)$ , and since  $(L_+^Q)^{kp+1} \subseteq R_+^k L_+^Q$  by Lemma 2.1, we get that  $\tau_A^G(m) = \tau_B^Q(m) \in (R_+^k L_+^Q) \cap R_+$ , but for any  $f \in (R_+^k L_+^Q) \cap R_+$  we have  $f = \frac{1}{[G:B]} \tau_A^G(\tau_B^A(f)) \in \tau_A^G(R_+^k \tau_B^A(L_+^Q)) \subseteq R_+^{k+1}$ , a

contradiction. As a result  $\Phi(m)|_B = (1^t, 3^s)$  by Proposition 9.2, where  $t > s$  can be assumed and  $t + s = 4pk + 2$ . Accordingly  $m$  has a factorization

$$m = m_1 \cdots m_l \quad (11)$$

where  $\Phi(m_i)|_B = (1, 3)$  for  $i \leq s$  and  $\Phi(m_i)|_B = (1^4)$  for  $s < i \leq l$ , so that  $l = s + \frac{t-s}{4}$ . Consider the sequence  $S := (\theta(m_1)|_C, \dots, \theta(m_l)|_C)$ ; it contains at most one occurrence of 0, for otherwise  $m \in (L_+^A)^2 L_{\geq 4pk-6}^A \subseteq R_+ L_{>\beta_{k-1}(G)}^A$  by Lemma 2.1, hence  $\tau_A^G(m) \in R_+^{k+1}$ , a contradiction. Moreover  $S$  cannot be factored into  $2k + 1$  zero-sum sequences over  $\hat{C}$ , for otherwise  $\tau_A^G(m) \in R_+^{k+1}$  follows again as  $m \in (L_+^A)^{2k+1} \in R_+^k L_+^A$ .

We claim that  $\{1, \dots, l\}$  can be partitioned into two disjoint, non-empty subsets  $U, V$  such that the monomials  $u = \prod_{i \in U} m_i$  and  $v = \prod_{i \in V} m_i$  are  $A$ -invariant,  $\tau_A^G(u^b v) \in R_+^{k+1}$  and  $\deg(v) > 4p(k-1) + 2 \geq \beta_{k-1}(G)$ . Under these assumptions  $\tau_A^G(m) = \tau_A^G(u)\tau_A^G(v) - \tau_A^G(u^b v) \in R_+^{k+1}$ , since  $\tau_A^G(v) \in R_+^k$  and this will refute our indirect hypothesis.

We will prove our claim by induction on  $\frac{t-s}{4}$ . Suppose first that  $\frac{t-s}{4} = 1$ , i.e.  $l = 2pk$ . Then  $\theta(m_1)|_C = \dots = \theta(m_l)|_C$  for otherwise  $S$  could be factored into  $2k + 1$  zero-sum sequences. Observe that if  $x$  is a variable in  $m_i$  and  $y$  is a variable in  $m_j$  where  $i \neq j$  and  $\theta(x)|_B = \theta(y)|_B$ , then  $\theta(x) = \theta(y)$ , since otherwise swapping the variables  $x$  and  $y$  yields another factorization as in (11) where  $l = 2pk$  but not all  $\theta(m_i)|_C$  are equal. We conclude that  $\Phi(m) = (e^{2pk+3}, (3e)^{2pk-1})$  for some generator  $e$  of  $\hat{A}$ . Then  $U := \{1, \dots, p\}$ ,  $V := \{p+1, \dots, l\}$  is the required bipartition, since  $\Phi(u^b v)$  is not similar to  $\Phi(m)$  and consequently  $\tau_A^G(u^b v) \in R_+^{k+1}$  by the above considerations.

For the rest it remains that  $\frac{t-s}{4} > 1$ , hence  $\Phi(m_{l-1})|_B = \Phi(m_l)|_B = (1^4)$ . If  $\theta(m_i) = 0$  for some  $i > s$ , say  $i = l$ , then choosing  $U = \{l\}$  gives the required factorization: indeed,  $\Phi(u^b v)|_B = (1^r, 3^s)$  where  $r - s < t - s$  and consequently  $\tau_A^G(u^b v) \in R_+^{k+1}$  by induction on  $\frac{t-s}{4}$ . If however  $S$  contains at least  $p + 1$  non-zero elements then using Lemma 6.2 we get a subset  $I \subset \{1, \dots, l-2\}$  such that  $|I| \leq p-1$  and  $\theta(\prod_{i \in I} m_i) = -\theta(m_l)$ . Now set  $U := I \cup \{l\}$ ,  $V := \{1, \dots, l-1\} \setminus I$  and observe that  $\Phi(u^b v)|_B = (1^r, 3^s)$  where  $r - s < t - s$ . So we are done as before, provided that  $|U| \leq p-1$  or there is an index  $i \in U$  such that  $i \leq s$ , because this guarantees that  $\deg(u) \leq 4p-2$ .

Otherwise it remains that  $l = p+1$ ,  $s = 1$  and  $\theta(m_1) = 0$ . Here  $m_1 = xy$ , where  $\theta(x)|_B = 1$  and  $\theta(y)|_B = 3$ . If there is a variable  $z$  in  $m_2 \dots m_l$  with  $\theta_C(z) \neq \theta_C(x)$ , then by swapping the variables  $x$  and  $z$  we get back to a case considered already. Thus  $\Phi(m/y) = ((1, c)^{4p+1})$  for a non-zero element  $c \in \hat{C} \cong Z_p$ , and  $\theta(y) = (3, -c)$ . Here  $U := \{1\}$ ,  $V := \{2, \dots, l\}$  is the required bipartition, because  $\Phi(u^b v) = ((1, -c), (3, c), (1, c)^{4pk})$ , and since  $c \neq -c$  it follows by the above considerations that  $\tau_A^G(u^b v) \in R_+^{k+1}$ .  $\square$

## 10 Proof of the main result

We shall use for the semidirect product of two cyclic groups the notation:

$$Z_m \rtimes_d Z_n = \langle a, b : a^m = 1, b^n = 1, bab^{-1} = a^d \rangle \quad \text{where } d \in \mathbb{N} \text{ is coprime to } m$$

**Proposition 10.1** (Burnside 1894, see for example [1] ch. IV.4). *If  $G$  is a finite  $p$ -group with a cyclic subgroup of index  $p$  then it is one of the following:*

1.  $Z_{p^n} \quad (n \geq 1)$
2.  $Z_{p^{n-1}} \times Z_p \quad (n \geq 2)$
3.  $M_{p^n} := Z_{p^{n-1}} \rtimes_d Z_p \quad d = p^{n-2} + 1 \quad (n \geq 3)$
4.  $D_{2^n} := Z_{2^{n-1}} \rtimes_{-1} Z_2 \quad (n \geq 4)$
5.  $SD_{2^n} := Z_{2^{n-1}} \rtimes_d Z_2 \quad d = 2^{n-2} - 1 \quad (n \geq 4)$
6.  $Dic_{2^n} := \langle a, b \mid a^{2^{n-1}} = 1, b^2 = a^{2^{n-2}}, bab^{-1} = a^{-1} \rangle \quad (n \geq 3)$

Let  $H$  be one of the 2-groups in the above list,  $\langle a \rangle$  an index 2 subgroup in  $H$ , and  $b \in H \setminus \langle a \rangle$ , so that  $H = \langle a, b \rangle$ . If  $H$  is a 2-group as in case (3)–(6) of Proposition 10.1 then for any odd integer  $r > 1$  it is customary to denote by  $M_{r2^n}$ ,  $D_{r2^n}$ ,  $SD_{r2^n}$ ,  $Dic_{r2^n}$  the group  $Z_r \rtimes_{-1} H$ , where  $b \in H$  acts on  $Z_r$  by inversion  $x \mapsto x^{-1}$  and  $\langle a \rangle$  centralizes  $Z_r$ .

**Proposition 10.2.** *Any finite group containing a cyclic subgroup of index two is isomorphic to*

$$Z_s \times (Z_r \rtimes_{-1} H)$$

where  $r, s$  are coprime odd integers, and  $H$  is a 2-group in Proposition 10.1.

*Proof.* Let  $G$  be a finite group with an index two cyclic subgroup  $C$ . Then  $C$  uniquely decomposes as  $C = Z_m \times Z_{2^{n-1}}$  for some odd integer  $m > 0$  and  $n \geq 1$ . As  $Z_m$  is a characteristic subgroup of  $C$ , it is normal in  $G$ . Thus by the Schur-Zassenhaus theorem  $G = Z_m \rtimes H$  for a Sylow 2-subgroup  $H$  of  $G$ . Moreover, the characteristic direct factor  $Z_{2^{n-1}}$  is also normal in  $G$ , hence we may suppose that it is identical to the index two cyclic subgroup  $\langle a \rangle \leq H$  (as the automorphism group of  $H$  acts transitively on the set of index two subgroups of  $H$ ). Now  $Z_m$  decomposes uniquely as a direct product  $Z_m = P_1 \times \cdots \times P_l$  of its Sylow subgroups. After a possible renumbering we may assume that  $H$  centralizes  $P_1, \dots, P_t$ , and  $H/\langle a \rangle$  acts on  $P_{t+1}, \dots, P_l$  via the automorphism  $x \mapsto x^{-1}$ . Setting  $Z_s := P_1 \times \cdots \times P_t$ ,  $Z_r := P_{t+1} \times \cdots \times P_l$  we obtain the desired conclusion.  $\square$

**Theorem 10.3.** *If  $G$  is a non-cyclic group with a cyclic subgroup of index two then*

$$\beta_k(G) = \frac{1}{2}|G|k + \begin{cases} 2 & \text{if } G = Dic_{4n}, n \text{ even} \\ & \text{or } G = Z_r \rtimes_{-1} Z_4, r \text{ odd} \\ 1 & \text{otherwise} \end{cases}$$



*Proof.* If  $G$  is any group with a cyclic subgroup  $A = \langle a \rangle$  of index 2, then Theorem 3.3 gives us the following lower bound:

$$\beta_k(G) \geq \beta_k(A) + D(G/A) - 1 = k|A| + D(Z_2) - 1 = \frac{1}{2}|G| + 1$$

To establish the precise value of the generalized Noether number  $\beta_k$  for these groups, by Proposition 10.2 we will have to consider the groups of the form  $G := Z_s \times (Z_r \rtimes_{-1} H)$  where  $H$  is one of the groups of order  $2^n$  listed in Proposition 10.1. In all these cases  $\beta_k(G) \leq \beta_{sk}(Z_r \rtimes_{-1} H)$  by Lemma 2.1.

(1) If  $H = Z_{2^n}$  then by Theorem 8.4 we have  $\beta_k(G) = 2^{n-1}rsk + 1$  except if  $n = 2$  and  $s = 1$ , in which case  $\beta_k(G) = 2^{n-1}rsk + 2$

(2) If  $H = Z_2 \times Z_{2^{n-1}}$  by the isomorphism  $Z_r \rtimes_{-1} (Z_2 \times Z_{2^{n-1}}) \cong Z_{2^{n-1}} \times D_{2r}$  we get from the application of Lemma 2.1 and Corollary 5.6 that

$$\beta_k(G) \leq \beta_{sk}(Z_{2^{n-1}} \times D_{2r}) \leq \beta_{2^{n-1}sk}(D_{2r}) \leq 2^{n-1}rsk + 1 \quad (12)$$

(3) If  $H = M_{2^n}$  then the group  $Z_r \rtimes_{-1} M_{2^n} = M_{2^n r}$  will contain a subgroup  $C = \langle a^2, b \rangle \cong Z_{2^{n-2}} \times D_{2r}$ . The subgroup  $N := Z_s \times C$  has index 2 in  $G$  and falls under case (2), hence by Lemma 2.1 and case (2) we have

$$\beta_k(G) = \beta_{2k}(N) = 2^{n-1}krs + 1 \quad (13)$$

(4) If  $H = D_{2^n}$  then  $G = Z_s \times D_{2^n r}$  and we are done by Corollary 5.6

(5) If  $H = SD_{2^n}$  then the group  $Z_r \rtimes_{-1} SD_{2^n} = SD_{2^n r}$  contains a subgroup  $B = \langle a^2, b \rangle \cong D_{2^{n-1}r}$ . Observe that  $B$  is a normal subgroup, as it has index 2, hence by Lemma 2.1 and Corollary 5.6 we get that

$$\beta_k(G) \leq \beta_{sk}(SD_{2^n r}) \leq \beta_{2sk}(D_{2^{n-1}r}) \leq 2^{n-1}rsk + 1 \quad (14)$$

(6) If  $H = Dic_{2^n}$  then for  $n = 2$  we get back to case (2), as  $Dic_4 = Z_2 \times Z_2$ ; if however  $n \geq 3$  then the quaternion group  $Q$  is a subgroup of index  $2^{n-3}r$  in  $Z_r \rtimes_{-1} H$ , therefore by Proposition 9.1 we have  $\beta(G) = 2^n rsk + 2$  if  $s = 1$  and for  $s > 1$  we get using Lemma 2.1 combined with Theorem 9.3 that for any prime  $p$  dividing  $s$ :

$$\beta_k(G) \leq \beta_{k2^{n-3}r}(Z_s \times Q) \leq \beta_{k2^{n-3}rs/p}(Z_p \times Q) \leq 2^{n-1}rsk + 1 \quad (15)$$

With this all possibilities are accounted for and our claim is established.  $\square$

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